Defect Inspection Challenges and Solutions for Ultra-Thin SOI

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This paper will explain the challenges and solutions for ultra thin SOI inspection using a laser light scattering based system. The impact of reflectivity on haze, sizing and minimum threshold will be detailed. We will show how the required sensitivity for 28nm (and beyond node) SOI inspection was achieved using a commercially available unpatterned DUV inspection system. We will also study improvements in defect classification.

I. INTRODUCTION

Fully Depleted (FD) devices are a most attractive option for next technology nodes, starting at 28nm and beyond, since the combination of ultra thin SOI and buried oxide (BOX) films greatly improves short channel effects and Vt matching, while offering a low variation solution compared to alternatives [1]. Moreover, these devices enable the modulation of Vt via back bias [2].

The foundation of the Planar-FD technology is Ultra Thin SOI (called UTBOX) substrates, for which the SOI can be thinned down to 10nm and BOX layers to 25nm [3]. A 12nm SOI / 25nm BOX substrate (UTBOX25) is first targeted for the 28nm technology node. Other substrate options with thinner BOX and/or a strained SOI layer are identified to support 20nm and beyond technologies and are merged in the so-called FD2D (Fully Depleted 2 Dimension) SOITEC product family [4]. The most widely used inspection systems for SOI inspection utilize scattered laser light to detect wafer surface defects. For inspection using these systems, problems can occur when the top Si thickness is thinner than the wavelength penetration depth: it results in interferences and different reflectivities, unique for each stack, making the layer difficult to analyze. We will discuss how SOITEC faced the challenge of inspecting FD2D SOI products, and how a new generation unpatterned inspection system provided the solution.

In addition, advanced classification capabilities from KLA-Tencor, that combine haze information and defect type, were used to classify typical SOI defect types such as voids, stains and scratches, and results showed exceptional accuracy and purity. This information, collected at the inspection step, should help improve manufacturing yield without the need for additional reviews.

II. CURRENT LIMITATIONS

A. *Thickness impact on haze*

Absorption of light is driven by the n & k values from silicon, and for a given wavelength, there is a thickness below which silicon doesn't absorb light. When stacking a silicon layer on top of an oxide/silicon stack, interference will occur. This phenomenon will impact the light scattered by the surface and by the defects and will therefore require different inspection conditions for each substrate type.

At the SOI top silicon thickness used in FD2D SOI, no laser based inspection systems available in the field can prevent the interference effect. The interference artifact is evident in the haze data collected by the tool. Haze is the low frequency background scatter signal, proportional to the quantity of light scattered by the wafer surface. On thin films, thickness of transparent films and surface characteristics like micro-roughness are the parameters that drive the amount of haze.

Fig.1 is a graph of the surface haze obtained with a UVwavelength laser-based inspection system (KLA-Tencor's Surfscan® SP2). Wafers with different buried oxide were successively thinned from 40nm down to 7nm. The haze rises and then falls slowly as the top thickness decreases below 35nm, and sharply increases below a thickness of 15nm. Therefore, below the critical thickness of 35nm, haze data will be sensitive to both top layer silicon thickness and surface roughness. Along the 3 thickness combination, UTBOX25 (12nm of silicon over 25nm of oxide) is the most unfavorable case, showing more than 3 times higher haze than product with 10nm of buried oxide, even if for device performance and integration reasons, it is the substrate selected for FDSOI introduction at 28nm node.

Therefore inspection capability needs to be adapted in order to provide the best performance on this specific thickness combination.

We also wish to use the haze value as a metric to evaluate the surface roughness only, and therefore were seeking a way to minimize the effects of the top layer thickness on haze.

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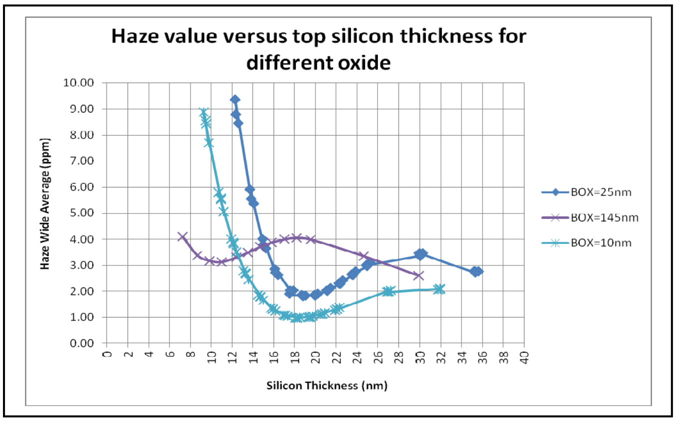

Figure 1. Haze versus thickness of top silicon layer of FD UTSOI substrate, as measured by haze channel of Surfscan SP2 system

Models predict a higher absorption at shorter inspection wavelengths, which would result in a decrease in critical thickness, the thickness below which the haze value is sensitive to stack thickness. When we re-ran the experiment using a Surfscan SP3 system, which has a DUV wavelength versus the UV wavelength on the Surfscan SP2 system, we observed that the haze variation arising from stack thickness was not an issue until the stack thickness reached 20nm. The haze from top silicon layers greater than 20nm was not affected by stack thickness.

When setting up inspection thresholds, the ratio between the defect signal and the local noise needs to be higher than 2:1 in order to guarantee repeatable detection. This local noise is proportional to the square root of the average haze; higher haze directly drives higher noise, limiting the minimum threshold and thereby, the sensitivity of the inspection.

In Fig.2 we plotted the threshold achieved (defined using signal to noise ratio rule of 2:1) using a common inspection tool, for different substrates showing different haze values (each point represent different wafer). All these substrates show the same surface roughness (as measured by Atomic Force Microscope (AFM)), so the average haze variation is directly related to the change in the top-level silicon thickness. We can see that the threshold curve and the haze noise curve follow a similar trend.

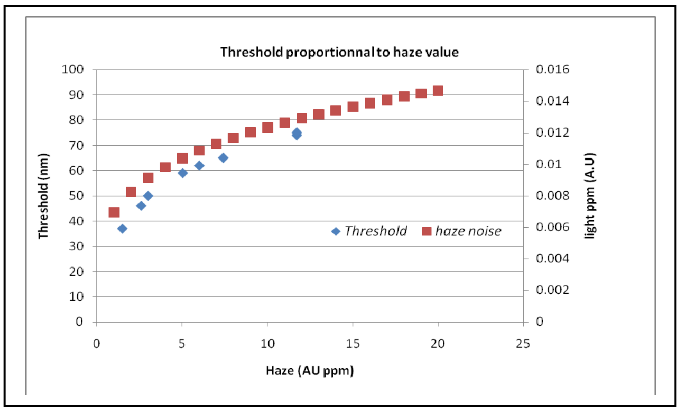

Figure 2. Minimum inspection threshold versus haze value

The experimental data demonstrates that from the haze value we can set the minimum inspection threshold for a given layer or substrate product. We are facing strong limitations due to the effect of the reflectivity when top silicon layer thickness is below 20nm.

B. Reflectivity impact on defect sizing

When top silicon layer thickness is below the critical value, in general around 12nm for FD UTSOI wafer, the reflectivity also impacts the scattering from the defect. Fig.3 shows the response of Polystyrene Latex (PSL) spheres of different sizes deposited on top of two different thin SOI products: the difference between the responses can be up to 20% and drives dramatic sizing errors. Measurements have been done using the Surfscan SP3 and the KT standard Si film curve.

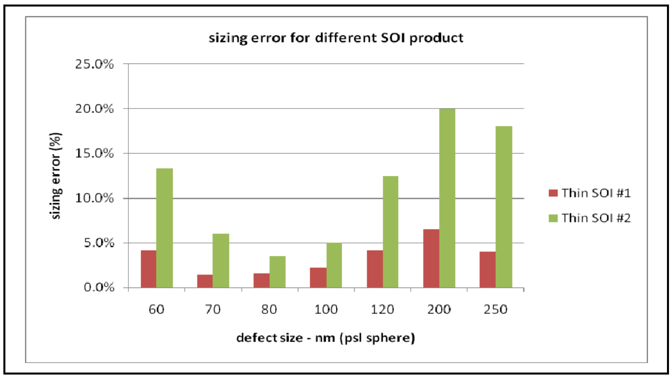

Figure 3. Defect sizing error for different substrate products, demonstrating the necessity for specific calibration curves.

For this reason a specific film curve needs to be used for each product to ensure correct sizing of the defects. It is developed by deposition of different sizes of calibrated PSL spheres on a representative substrate. Use of specific film curves is important to be able to compare inspectabilities of different substrate products, and know if they are compatible with the most advanced chip technologies.

C. Tool limitation

In order to meet defect sensitivity requirements, system characteristics play an important role. The scattering intensity of a defect ($P_{scattering}$) is strongly affected by the Intensity ($I_{incident}$) and the wavelength (λ) of the incident beam, as seen in Equation (1) below. Other parameters are defect dependant (Defect size (d) and refractive index for the defect material composition (n))

$$P_{scattering} \propto \frac{d^6(n^2-1)^2}{\lambda^4} I_{incident} \quad (1)$$

Using the Surfscan SP3 system with its shorter wavelength, SOITEC showed a strong improvement in minimum threshold (best defect sensitivity) achievable across various substrate products, when compared with the previous-generation, longerwavelength Surfscan SP2. Fig.4 shows the improvement comparing the two tool generations while keeping throughput constant (High Throughput mode).

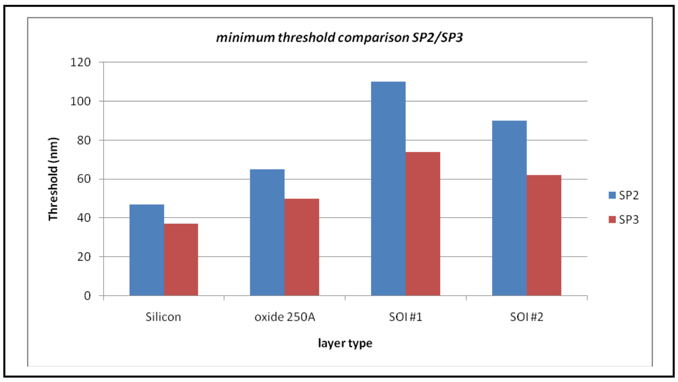

Figure 4. Minimum achievable threshold (best defect sensitivity) of Surfscan SP2 versus Surfscan SP3 on various substrate products

Moving to the latest generation inspection system helped SOITEC inspect its products at the best sensitivity possible. The level reached, however, is still not sufficient to comply with the 22nm node and beyond for FDSOI.

III. FD UTSOI INSPECTION SOLUTION

A. Improving inspection sensitivity

In order to achieve the required sensitivity for thin UTSOI substrates, a special aperture can help. The scattering equation determines that scattering direction depends on the surface spatial frequencies. Fig.5 represents this phenomenon. The reflections from defects and surface topography are composed of different spatial frequencies, so will not scatter light in the same direction.

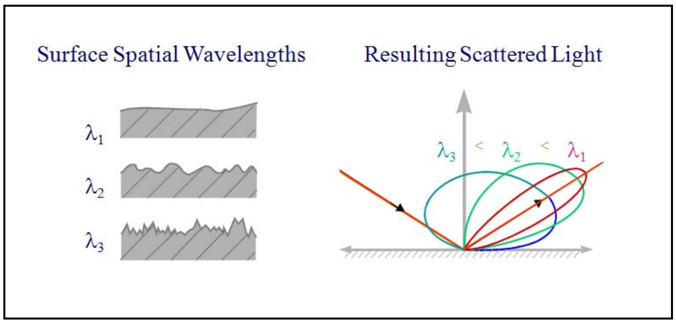

Figure 5. Direction of light scattering depends on spatial wavelengths of the surface topography.

Apertures can be introduced into the beam to block scattering from surface components. The difficulty of this approach is to ensure that defects of interest do not scatter in directions blocked with the apertures. During the development of the new UTBOX25 optics, it was verified that we were not losing defect signal by systematically comparing the defects detected using the aperture and without the aperture, helped with SEM review to identify the lost defects and their types. One specific defect type with morphology really close to the surface scattering (mainly smoothed defect) drove the need to try multiple types of apertures. In the end the best compromise between minimum haze/surface signal and maximum capture rate for all defect types of interest was found. Fig.6 schematically illustrates an example of a challenging defect type, with a scattering distribution in a tangential direction.

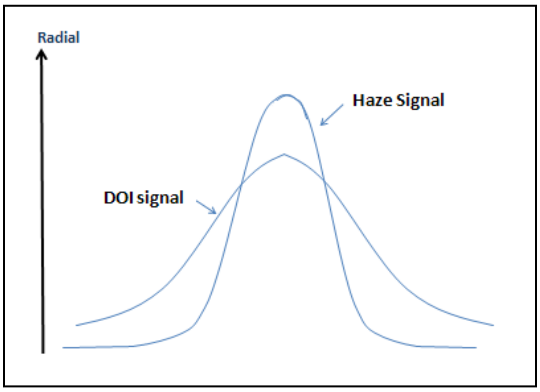

Figure 6. Schematic illustration of a difficult detection problem, in which the light scattering distribution is similar between haze and defect

After systematic investigation, the optimal aperture was named XFS_J, created for UTSOI products having top silicon layer thickness of 12nm and oxide thickness of 25nm; and XFS_G, created for products having thick top silicon layers. This helped produce a decrease in the minimum detection threshold to 50nm, versus a starting point at 74nm for the 12nm over 25nm product. This improvement is really important for SOITEC, as it has been achieved on the stack having the most challenging reflectivity. Fig. 7 shows the percent DOI (Defect Of Interest) detection and minimum thresholds for the different types of apertures tested. Aperture #3 was selected. This improvement allows UTBOX25 to be inspected at the level required for the 22nm technology node.

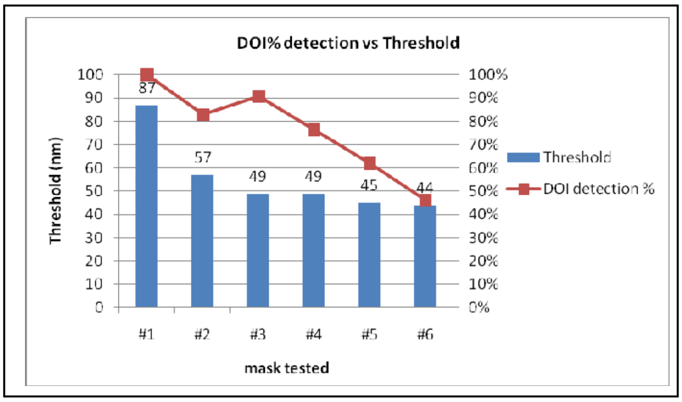

Figure 7. Thresholds achieved for different apertures with corresponding DOI capture

As part of the ongoing investigation, we will explore how the aperture can be adapted to different stacks, for example, when oxide thickness is reduced from 25nm to 20nm. Initial work seems to confirm that as long as spatial frequencies do not change dramatically, apertures developed are still valid.

A generic SOI recipe has been developed that will be available with all Surfscan SP3 systems in the field. This recipe, or best known method (BKM), uses the aperture best suited for UTBOX25, allowing a 50nm threshold; a film curve designed for correct defect sizing; and typical classification algorithms.

B. Advanced defect classification

Unpatterned wafer defect inspection systems traditionally give a limited amount of information about defect type. Algorithms are mainly based on spatial distribution of defects on the wafer on which shape recognition is performed (slip line, cluster or scratch). Defect type information is obtained by reviewing the wafer on a SEM defect review system, a procedure which is time consuming and highly manual, especially for sub-50nm defects.

With advanced substrate manufacturing, quick feedback is required to limit impact on manufacturing yield and improve learning. The new inspection system introduces embedded algorithms and a new and non-disruptive classification method.

Analysis of the inspection results shows that some defects can be seen in two different channels: as a cluster in the Dark Field (DF) channel and as a bright spot in the haze channel. A defect type falling into this category is voids, specific locations at which the top silicon layer is not transferred. A void is big enough to be detected as an "area defect," but it cannot be differentiated from other big defects like particles which can be removed during a chemical clean. There is a huge interest in improving SOI quality by being able to distinguish this defect from other types. Fig.8 below shows the same location on the wafer seen from the two different channels. The defect seen in DF and in haze is a void while the defect seen only in DF is a particle.

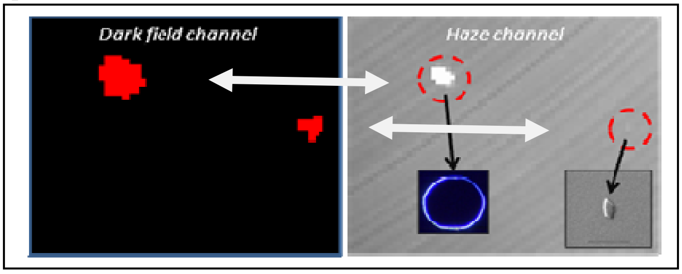

Figure 8. DF and haze channels showing void (upper left) and particle (middle right) defects.

With previous-generation inspection systems, individual defects can be detected in DF or haze channels, but no capability is available to merge the information from the DF and haze channels to identify a defect with a unique classification code. The new Surfscan SP3 inspection system offers integration of SURFmonitor^{TM}, a subsystem capable of quantitative analysis of high resolution haze images. SURFmonitor allows such dual-channel processing and makes the information available for each wafer without additional reprocessing. SURFmonitor results can also be used for wafer sorting.

SURFmonitor introduces a flexible method of classification called "Rule Based Binning" (RBB). The following recipe helps to enable this classification:

- Haze defects are detected using specific algorithms (called APD).
- A first application of RBB is used to eliminate nuisance defects; defects of interest are round, while nuisance defects can be long.
- In parallel, traditional "cluster" classification is done in the DF composite map.
- A second RBB is applied to merged defects, i.e. cluster defects from the Dark Field data and APD from the haze that appear at the same location. A special class code is given for such defects, which are considered voids.
- Void information is sent to the automation host to enable wafer sorting based on specification.

Fig.9 below represents the flow:

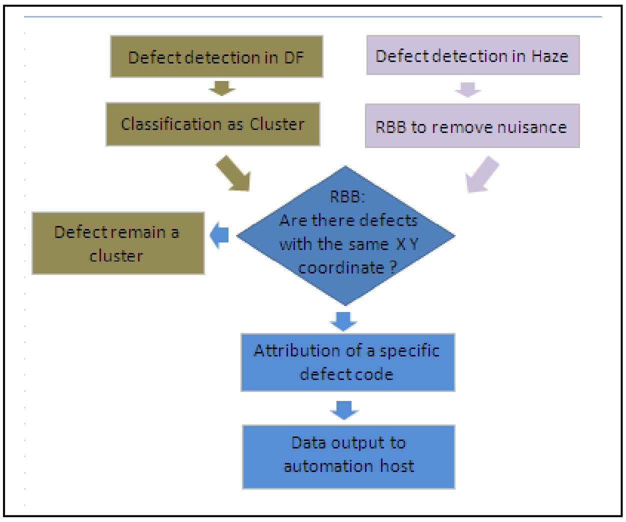

Figure 9. Schematic of the defect classification process, combining Rules-Based Binning and traditional classification methods.

We were able to achieve excellent accuracy and purity results with this classification process: more than 90% of the voids can be classified correctly, with classification purity higher than 95%. The limiting factor is the size of the voids, which can prevent their detection in the haze channel.

Another unique classification which has been tested refers to residue classification. These defects have a unique signature that absorbs more light than the background, so that the defect appears dark. Standard algorithms are designed to detect "positive" variation, pixel to pixel. A new algorithm available in SURFmonitor divides the wafer map into small grid squares, and haze pixel statistics are computed inside each square. Statistics include max, mean, min, and standard deviation. For squares with dark defects, we apply RBB to check the ratio of the minimum value to the median value, flagging bad squares and reporting them on the map. These results are available for automation. Fig. 10 shows a representative haze map with a residue defect, and the associated bad square.

Figure 10. Haze map with residue defect.

The two examples described in this paper support our finding that the new inspection system and its new capabilities have helped our process teams to better identify defectivity on the wafer. The new tools also have helped us improve overall wafer quality by enabling sorting and grading based on additional parameters.

IV. CONCLUSION

New products like UTBOX25 introduce new challenges for inspection of unpatterned substrates. We have been able to solve these challenges and as a result, enable 50nm and below inspection.

The use of the latest generation unpatterned wafer inspection system, the KLA-Tencor Surfscan SP3, demonstrated that wavelength reduction together with greater laser power are the key parameters to reach lower threshold. The development of a unique aperture was a key element to face challenges related to high reflectivity due to the low SOI thickness used on UTBOX25.

With new information available across the different channels from this inspection system, being able to merge this information with the integration of the SURFmonitor data helped in the development of a new and accurate classification scheme.

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